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North Atlantic warming and the retreat of Greenland's outlet glaciers

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Mass loss from the Greenland ice sheet quadrupled over the past two decades, contributing a quarter of the observed global sea-level rise. Increased submarine melting is thought to have triggered the retreat of Greenland's outlet glaciers, which is partly responsible for the ice loss. However, the chain of events and physical processes remain elusive. Recent evidence suggests that an anomalous inflow of subtropical waters driven by atmospheric changes, multidecadal natural ocean variability and a long-term increase in the North Atlantic's upper ocean heat content since the 1950s all contributed to a warming of the subpolar North Atlantic. This led, in conjunction with increased runoff, to enhanced submarine glacier melting. Future climate projections raise the potential for continued increases in warming and ice-mass loss, with implications for sea level and climate.

Mass loss from the Greenland ice sheet (GrIS) quadrupled from 1992–2001 (51 ± 65 Gt yr^{-1}) to 2002–2011 (211 ± 37 Gt yr^{-1}), contributing to a rise in global mean sea level of 7.5 ± 1.8 mm from 1992 to 2011, roughly twice that from the Antarctic ice sheet[1,2] (Box 1). At present, GrIS mass loss accounts for one quarter of the observed global sea-level rise[3]. Persistent ice loss from Greenland is also increasing the freshwater input into the North Atlantic. Conventionally, Greenland's freshwater discharge (Box 1) into the North Atlantic has been assumed to be negligible compared with the freshwater export from the Arctic Ocean[4]. However, a recent study[5] argues that the cumulative freshwater anomaly discharged by the GrIS since 1995 amounts to a third of Arctic-origin freshwater anomalies that have disrupted dense water formation in the North Atlantic in the past. GrIS mass loss therefore may soon affect the Atlantic meridional overturning circulation (AMOC; Box 1), a key component of the climate system.

GrIS mass loss is due, in equal parts, to two processes[6,7] (Fig. 1a). First, negative surface mass balance (Box 1) is attributed to a persistent increase in surface melt in southeast and west Greenland[6,8]. Second, increased ice discharge resulted from the speed up, thinning and retreat of multiple marine-terminating glaciers (in contrast to those terminating on land[9]) in southeast and west Greenland that began in the mid-1990s[10,11] (Fig. 2a) and spread to the northwest (Fig. 2b) in the mid-2000s[12]. Whereas many of the southern glaciers have slowed down since their peak speeds in 2005, most continue to flow faster than in the mid-1990s, although there is variation between glaciers in the same area[13].

The widespread and synchronous nature of changes in both surface mass balance and ice discharge are indicative of a response to external forcings, and consistent with observations of atmospheric[14] and oceanic warming[15] (Fig. 1b, c) over and around Greenland. The forcing responsible for the decrease in surface mass balance is evident[6,8]: changes in precipitation and rising air temperatures have resulted in increased surface melting over the ice sheet[14,16,17]. The mechanisms and forcings behind the increased ice discharge, however, remain elusive.

Glacier speed-up resulted from initial retreat[11,18] of the marine termini (Fig. 2a, b) that decreased the resistance to ice flow, increased calving and thinning[19], and led to further retreat[20–24]. One leading hypothesis to explain the initial retreat of the glaciers involves an increase in submarine melting at the ice–ocean interface[23,25,26]. Ocean forcing is also invoked as a potential driver of changes in the ice mélange[27] (Fig. 2a). Finally, changes in sea-surface temperatures around Greenland have been correlated to changes in coastal air temperatures and, in turn, to changes in runoff[16], implying that ocean-induced localized atmospheric changes may be affecting the GrIS.

When initially proposed, the above-mentioned hypotheses were based on the observation that the glaciers began to speed up and retreat at the same time as the waters off west Greenland warmed rapidly[28]. The pervasive lack of ocean data near the glaciers at that time and our limited understanding of the mechanisms of ice-sheet–ocean interaction made it difficult to examine its plausibility. Since then, multiple field, modelling and theoretical studies have greatly advanced our understanding of how ocean variability affects the glaciers' margins.

In this Review we discuss these advances and conclude that warming of the subpolar North Atlantic (SPNA) ocean and atmosphere led to an increase in submarine melting of the glaciers. We discuss the context of warming of the SPNA (which is unprecedented in the historical record, except for a similar warm period in the 1930s) in terms of climate variability over the North Atlantic sector. We argue that the SPNA warming cannot be attributed to a single mode of atmospheric or oceanic variability. Rather, present-day warming is due to the superposition of these modes on a long-term ocean warming trend. This Review complements other articles on the ice sheet's response to ocean forcing[23,25,26], by focusing on the ocean dynamics around Greenland and its larger scale context.

From basin to boundary layer scales

The subject of ice-sheet–ocean interactions in Greenland described in this Review involves a range of scales, from the basin-wide North Atlantic (1,000 km scale) to the turbulent boundary layer at the ice–ocean interface (millimetre scale). We present the observational evidence for the physical processes that act on, and connect, these scales.

Continental shelf hydrographic variability

The increase in ice discharge that started in the mid-1990s is associated with the retreat of glaciers at the margins of the SPNA and its extension into Baffin Bay (between west Greenland and the Canadian Arctic Archipelago; Fig. 3a). The circulation around the SPNA is a cyclonic (anticlockwise) gyre with warm waters from the subtropics flowing

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BOX 1

Ice glossary

- **Units** Typical units used by the glaciological and oceanographic communities are mass loss in gigatonnes per year (Gt yr^{-1}), global mean eustatic sea-level rise in millimetres per year, and volume transport in sverdrups (1 Sv = 10^6 m^3 s^{-1}). Conversion factors between these are: 1 Gt yr^{-1} = 2.8×10^{-3} mm yr^{-1} = 3.17×10^{-5} Sv.
- **Estuarine-driven circulation** The buoyancy-driven circulation associated with the entrainment of ambient water into the plume as it rises along the ice face and flows out of the fjord[47,49].
- **North Atlantic oscillation (NAO)** A leading pattern of atmospheric variability measuring the sea-level pressure differences between weather stations in the Azores and Iceland[66].
- **Atlantic multidecadal oscillation (AMO)** A mode of oceanic variability expressed as the sea-surface temperature (SST) anomaly over the North Atlantic[70,71].
- **Atlantic Meridional overturning circulation (AMOC)** Zonally (west–east) integrated and vertically accumulated volume (or mass) transport in the Atlantic.
- **Freshwater discharge** The sum of solid ice discharge due to calving and liquid subglacial discharge from surface- and sub-glacial melting[5,6].
- **Ice mélange** A mixture of icebergs and sea ice found in front of the terminus of many Greenland glaciers that may affect calving[27].
- **Glacial isostatic adjustment (GIA)** Geodynamic and geodetic effects associated with ice-sheet mass loss, including visco-elastic rebound due to unloading of the mantle, adjustment of Earth's angular momentum and rotation, and change of Earth's gravity field (geoid) owing to mass redistribution[86].
- **Mass balances**
Total mass balance (MB) = surface MB (SMB) − discharge (D); SMB = accumulation (A) − runoff (R); freshwater flux = R + D.

around the continental slopes of Greenland and North America encircling the colder, denser interior of the SPNA[29,30]. Cold, fresh water from the Arctic flows around Greenland's 200–300 m deep continental shelves, partially buffering Greenland's coast from the warm, Atlantic waters[31] (Fig. 3a). The glacier retreat coincided with a rapid warming of the SPNA that began in the mid-1990s[15,29] and that continues today[32] (Fig. 3b–d). The SPNA change is manifested in a warming of the upper 500–1,000 m of the waters off west Greenland, including the continental shelf[28,33,34] (Fig. 1b) and extending to Baffin Bay[35]. Data from the continental shelves of southeast Greenland are limited, but repeated annual hydrography across the Irminger Sea shows an extensive thickening of the Atlantic layer around the mid-1990s and suggests a similar warming of the shelf waters[30]. The continental shelf warming is probably associated with more frequent intrusions of (warmer) Atlantic water in the deep troughs that stretch across Greenland's shelves[31]. Whether these have a surface signature[36] remains unclear.

Exchanges between fjord and continental shelf

Greenland's large marine-terminating glaciers are typically grounded several hundreds of meters below sea level at the head of long (10–100 km), narrow (<10 km) fjords that connect them to the continental shelf (which we refer to in this Review as shelf; Fig 4). Data from the fjords preceding the SPNA warming are too scarce to provide information that, in conjunction with recent surveys, could be used to describe how the fjords responded to the shelf warming. A comparison of ocean properties from two summer surveys taken before and after the mid-1990s warming (1993 and 2004) in Kangerdlugssuaq Fjord, southeast Greenland, shows warming of fjord waters[37], but it is unclear to what extent differences between the two short surveys are representative of longer term changes in the fjord compared with the large weekly to inter-annual variability. Recently collected data from several fjords, combined with dynamical considerations, however, provide a consistent picture that offers insight into how the fjord properties may have changed in response to the SPNA warming. Surveys have shown that the fjords contain a thick layer of warm (0–4 °C, compared with the freezing point of seawater, roughly −1.9 °C) saline, subsurface Atlantic water beneath a layer of cold, fresh polar water (Fig. 4)[28,37–40]. The warmest Atlantic water is found in glacial fjords abutting the SPNA and Baffin Bay, whereas the coldest is found in glacial fjords abutting the Arctic Ocean in northern Greenland. This is consistent with variations in the mean Atlantic water properties on the nearby shelf and slope and reflects the distance (along its mean flow pathway) from the subtropical source region[41]. Along-fjord variations are relatively small, suggesting that Atlantic water is also found in the vicinity of the glaciers, although most of the surveys terminate about 10 km from the glaciers' edge because of the inaccessibility of this region (Fig. 2).

The similarities between the fjord and the shelf properties are consistent with the fact that the fjords typically have deep (>200 m) sills that allow for a relatively unobstructed exchange between the two[36,40,41]. This suggests that these fjords contained Atlantic water and

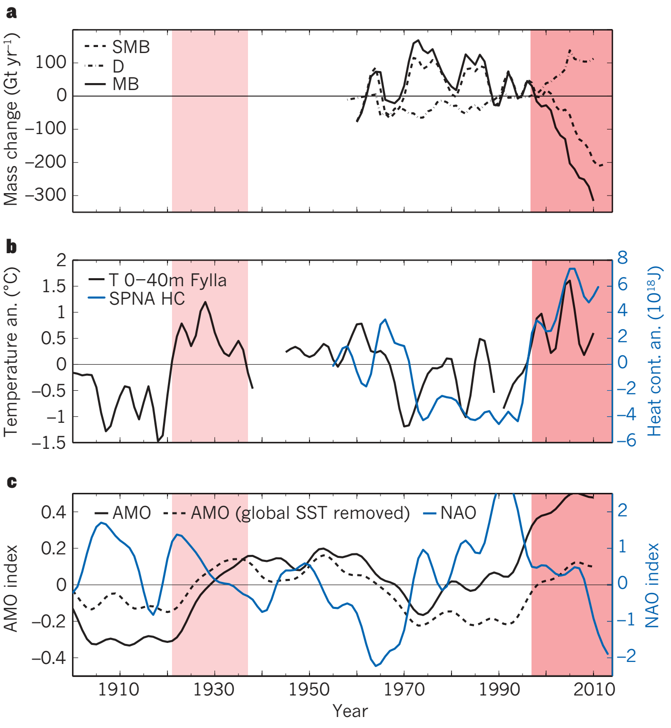

Figure 1 | Retreat of Greenland's outlet glaciers is occurring at a time when the waters of the subpolar North Atlantic are the warmest on record. **a**, Mass balance (MB), surface mass balance (SMB) and ice discharge (D) anomalies in gigatonnes per year based on refs 5, 6. **b**, Mean temperature anomaly (an.) of the upper 40 m at Fylla Bank, west Greenland[58] and heat content anomaly of the SPNA's upper 700 m[55]. **c**, Atlantic multidecadal oscillation (AMO) index anomalies with and without the global SST trend[71,73], and North Atlantic oscillation (NAO) winter index[66]. All time series have been extended to 2010 and 5-year low-pass filtered, and the mean with respect to the period shown has been removed. Recent glacier acceleration began in the late 1990s (dark shading), a similarly warm period occurred in the 1930s (light shading) with some evidence for glacier retreat of comparable magnitude.

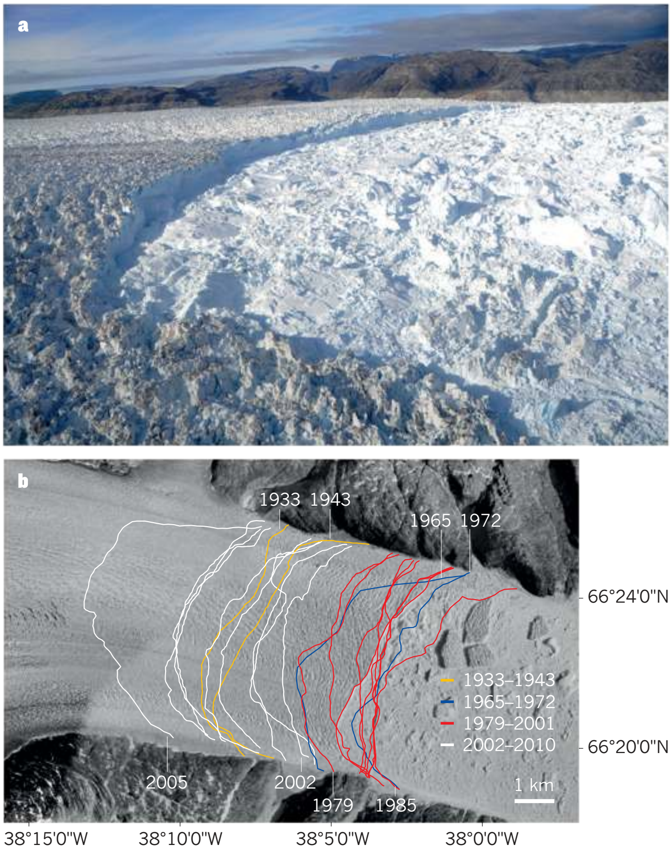

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Figure 2 | Retreat and thinning of Greenland's outlet glaciers. **a**, Helheim Glacier terminates in Sermilik Fjord, southeast Greenland. The glacier is grounded in 600 m of water and has a thick ice mélange. The light coloured lower reaches of the mountains show the glacier's extent before the early 2000s retreat. **b**, Helheim retreated more than 4 km between 2002 and 2005. The retreat was comparable only with that of the 1930s[58].

polar water even before the mid-1990s, although the Atlantic water layer was probably colder and thinner, given the colder conditions on the shelves. Fjord waters can be renewed ('flushed') through different processes (Fig. 4), including exchanges driven by the shelf circulation, tidal mixing, local winds and estuarine flows[42,43] (Box 1). How quickly and by what mechanisms the fjords' properties evolved from the pre- to the post-SPNA warming conditions remains poorly understood, owing to the lack of direct velocity measurements. The few that exist suggest fast currents and high-frequency (weekly) variability[42,43]. The limited moored measurements and repeat surveys, consistent with the fast flows, reveal property changes on sub-seasonal timescales[39,43,44], suggesting that even the large fjords have rapid flushing times, with responses to the proposed shelf warming within months.

Plume dynamics at the ice–ocean interface

A warming of the fjords does not simply translate into an increase in submarine melt. Indeed, the fjords' waters contain much more heat than the glaciers can extract (based on estimated upper bounds for total ice discharge derived from remote sensing[40]). This is because the heat exchange between the ice and the ocean depends on the turbulent exchange across a thin ice–ocean boundary and ultimately on molecular processes that make it fairly inefficient[45]. There are no direct observations for Greenland's glaciers but parallels with Antarctica, theory and models indicate that the boundary layer is dominated by one or more rising, buoyant plume or plumes driven by the release of fresh water from surface melting at the base of the glacier (subglacial discharge) and from submarine melting along the glacier face[46]. The exchange of heat and salt is thus largely dominated by the plumes' properties (temperature, velocity and, to a lesser extent, salinity[47]) which, in turn, are controlled by a number of oceanic (for example, far field velocity, temperature and salinity) and glaciological (for example, shape of the ice front or surface roughness) parameters in ways that are not fully understood.

One parameter that has emerged as a key factor affecting summer submarine melt rates is the amount and distribution of subglacial discharge. Observations of contrasting winter and summer conditions in the fjords have highlighted the importance of subglacial discharge[43,44,48]. Additional quantitative modelling studies have shown that an increase in subglacial discharge will lead to an increase in submarine melting[46,47,49–51]. Other fjord properties that influence submarine melt rates include warmer waters (which increase melt rates), its stratification (the large density difference between Atlantic water and polar water can cause the plume to equilibrate at the Atlantic-water–polar-water interface, thus limiting the vertical extent of submarine melting[47,48]), and its circulation (which can both affect the plume and is potentially a source of turbulent kinetic energy for mixing across the ice–ocean boundary).

Proposed mechanisms

From an oceanographic viewpoint, three types of mechanisms are directly implicated in glacier–ocean interactions: thermodynamic processes involved in melting at the calving front, circulation processes that modulate water masses at the calving front, and stress balance ('dynamic') perturbations resulting from the contact between the ice mélange and the calving front.

Submarine discharge and melting

Given the observed changes in the ocean and atmosphere in the mid-1990s there are at least two mechanisms that probably gave rise to increased submarine melt rates (Fig. 5a, b). First, the increase in Atlantic water on the shelves probably resulted in a warmer and thicker layer of Atlantic water in the fjords, both of which will increase submarine melt rates[47]. Second, an increase in subglacial discharge (due to anomalous surface melt[6]) would have increased summer melt rates[46,47,50,51]. The former may be referred to as melt-driven convection, the latter as convection-driven melting[46]. There are no direct observations of submarine melt rates for Greenland's glaciers (before or after the retreat started). Indirect estimates based on ice-divergence calculations for the Jakobshavn Isbræ are 228 ± 49 m yr^{-1} pre-speed up, with an estimated 25% increase due to warming ocean temperatures[52]. Summer estimates based on measuring the oceanic heat flux towards a glacier range from 26 to 1,400 m yr^{-1} (refs 38, 40, 42, 50), but these are highly uncertain given the unsteady nature of the circulation in the fjord and the assumption that all of the heat flux goes into melting.

Estuarine compared with intermediary fjord circulation

One unresolved issue, relevant to our understanding of how the submarine melt rate may have changed in the mid-1990s, is the extent to which the estuarine-driven circulation (Box 1), due to the release of submarine and surface melt from the glacier, is the dominant 'heat-transporting' circulation in Greenland's glacial fjords[16,38,47,50,52]. If this were the case, then an increase in subglacial discharge (and hence submarine melting) would increase the transport of heat towards the glacier and potentially further increase the submarine melting. At present, there is no evidence, however, that the estuarine-driven circulation governs the renewal of Atlantic water in the fjords. Numerical simulations have been instrumental in advancing our understanding of the relationship between the plume dynamics, the submarine melt rate and the fjord circulation[47,50,51,53,54]. However, covering the relevant spatial scales, from millimetres to tens of kilometres, is challenging even for the highest resolution models. Instead, models rely on parameterizations of unresolved processes, some of which are poorly constrained by observations[46,47]. Furthermore, fjord-scale simulations are sensitive to boundary conditions imposed at the fjord's mouth for which few measurements of variability exist, making it difficult to assess how shelf-driven variability influences submarine melting.

Ice mélange in the fjords

Unlike submarine melting, it is less clear how the warming of the SPNA may have affected the ice mélange — another proposed direct influence on the glaciers[27]. SPNA warming probably resulted in an increase in the subsurface Atlantic water temperatures in the fjords, but it is unclear what direct impact it had on the surface temperatures in the fjords and, hence, on the ice mélange. However, SPNA warming is highly correlated with an increase in the coastal air temperatures[16,17], which, in turn, may affect the structural integrity of the mélange. Changes in sea ice cover outside of the fjord may further affect the mélange.

Glacier retreat during the past century

The recent warming of the upper 1,000 m of the SPNA is unprecedented over the instrumental record of upper ocean temperatures (although a less pronounced warming occurred in the 1960s)[32,55] (Figs 1b, 3d). During the past century, warming comparable with that of recent decades only occurred in the 1930s as observed from temperature records of the upper 300 m of the North Atlantic[56]; sea-surface temperatures from the eastern subpolar North Atlantic[57]; temperatures (0–40 m depth) from Fylla Bank, west Greenland, 1870 to present[58] (Fig. 1b); and in the reconstruction of ocean temperatures at the surface and at 300 m from sediment cores in Disko Bay, west Greenland[59].

Records of glacier frontal position before continuous dedicated satellite radar observations became available (from 1991) are scarce. Cumulative evidence from several studies nevertheless suggests that the only time over the past century when glaciers in southeast and west Greenland retreated as much as in the present day was in the 1930s, consistent with the North Atlantic warming. These include the reconstruction of frontal positions of glaciers in southeast and west Greenland from photographs (for example, Fig. 2b) and remote sensing[59–61], and a reconstruction of calving variability over the past 120 years of one major southeast Greenland glacier from sediment cores[58]. Air temperatures over the ice sheet were also high in the 1930s[14], which, together with ocean warming, would also have led to an increase in submarine melting.

Causes of SPNA warming

The SPNA ocean warming that began in the mid-1990s is manifested as an increase in heat content of the upper 1,000 m (Fig. 3d) and has been associated with a slow down of the subpolar gyre[55,62]. The warming is attributed to the anomalous inflow of warm, salty, subtropical Atlantic water into the subpolar region[63] driven by shifting wind patterns over the North Atlantic[62,64]. These, in turn, are strongly correlated with the wintertime occurrence of large, quasi-stationary waves in the North Atlantic eddy-driven jet stream (atmospheric blocking) over Greenland and western Europe[64,65].

Although progress has been made in explaining SPNA warming, its connection to the large-scale variability of the coupled ocean–atmosphere system remains unclear. Several studies have linked the SPNA changes to the North Atlantic oscillation (NAO)[66,67], a dominant mode of atmospheric variability over the North Atlantic (Box 1), which switched from a persistent positive phase in the early 1990s to a negative or quasi-neutral phase until the mid-2000s (Fig. 1c). This inference is consistent with the expected warming of the subpolar and cooling of the subtropical North Atlantic during a negative NAO phase. This opposing behaviour has been used to explain the synchronous and opposite changes in upper ocean heat content anomalies of the subtropical and subpolar gyres from the 1950s to 2000s[67,68,32] (Fig. 3c, d), and has led investigators to conclude

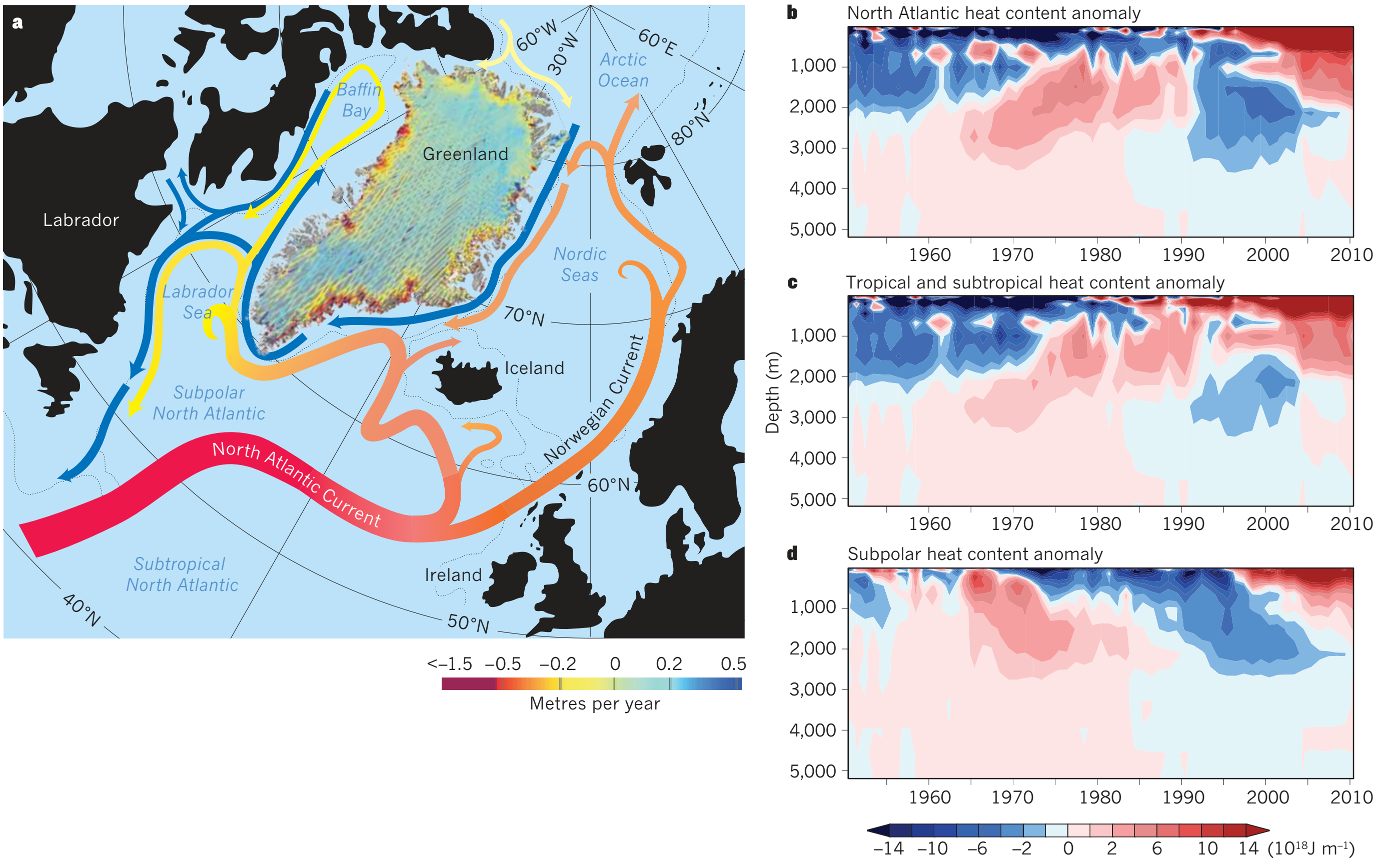

Figure 3 | Thinning of the Greenland ice sheet is concentrated at the margins of the subpolar North Atlantic. **a**, The large-scale ocean circulation around Greenland, indicating the major currents and basins. Atlantic-origin water pathways, red to yellow; Arctic-origin freshwater pathways, blue[41]. The dynamic thinning of Greenland is superimposed[19]. **b**, Heat content anomaly estimates in the North Atlantic as a whole and **c**, separated into tropical and subtropical and **d**, subpolar contributions over the period 1960–2010 (ref. 32). Extremely sparse observational coverage below 700 m depths over much of the period adds significant uncertainties.

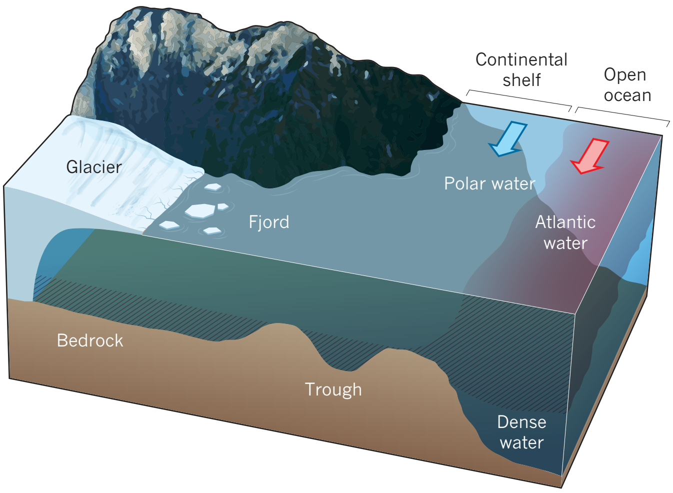

Figure 4 | Fjord and continental shelf exchanges. Warm and salty Atlantic waters (red) of subtropical origin, circulating around the subpolar North Atlantic reach Greenland's glacial fjords at depth (and hence the outlet glaciers) after crossing the continental shelf, where cold, fresh polar waters of Arctic origin flow close to the coast. The ocean-to-glacier link involves a wide range of space and time scales across regions with distinct dynamics.

that Atlantic water variability at Greenland's margins was linked to the NAO[28]. Recent studies, however, question the role of the NAO as a driver of the recent SPNA variability. In particular, statistical analysis suggests that much of the wind stress, SPNA heat content and sea-surface height anomalies cannot be attributed to the NAO[64,69]. NAO-driven variability cannot account for the recent simultaneous warming of the upper 1,000–2,000 m of the subpolar and subtropical North Atlantic that started in the late 1990s and has resulted in a large heat content anomaly over the entire North Atlantic (Fig. 3b).

On multidecadal timescales, the warming of the SPNA has a stronger correlation with the Atlantic multidecadal oscillation[55,56] (AMO), an index[70–72] that is associated with a range of climate processes including AMOC variability (Box 1). The absolute AMO contains a significant contribution from the global rise in SST[73] (Fig. 1c), but a significant correlation between the SPNA SST and the AMO persists even after the global rise in SST is subtracted[64]. In general, neither the sea-surface height variability of the SPNA nor the AMO, both of which are oceanic modes of variability, are connected in any simple way to atmospheric variability[74].

The emerging picture is that SPNA warming is largely due to increased inflow of warm, subtropical waters into the subpolar region. The subtropical ocean has been accumulating heat[75] (Fig. 3c), partly due to atmospheric warming[32], but it was only after the NAO emerged from its persistent positive phase that some of this heat was transported into the subpolar region. The persistence of wind patterns driving subtropical waters into the subpolar region, a warm AMO phase and the warming trend in the North Atlantic ocean[75] are all likely contributors to SPNA warming.

The future

The development of skilful predictive capabilities of ice-sheet–ocean interactions around Greenland will require an understanding of the relevant forcing factors and the physical processes that are responsible for Greenland's response, and consideration of the effect of the mass loss on the regional and global climate system. We briefly discuss several key observational and modelling challenges, which will require broad scientific community engagement across disciplines.

Identifying research requirements

The challenge at hand is cross-disciplinary, involving oceanographers, glaciologists, meteorologists, and palaeoclimate and climate scientists. Bringing the corresponding modelling and observational communities together is imperative and requires international collaboration at the researcher and agency levels. The first steps towards this goal were made in June 2013 through an international workshop on Greenland ice-sheet–ocean interactions in Beverly, Massachusetts, sponsored by the US Climate Variability and Predictability Research Program (US CLIVAR).

The details are subject to ongoing discussion, but an overall two-pronged approach to make progress has emerged[26]. First, dedicated process studies and field campaigns are needed, in which the available diverse observational assets are pooled, to shed light on the mechanisms described in 'Proposed Mechanisms'. The aim is to move from a qualitative to a quantitative description against which theory and numerical models can be tested, as a prerequisite for developing suitable parameterizations for climate models. One difficulty is whether there exists a 'representative system' to study, or whether different mechanisms require studying different systems. Second, quantitative understanding of the forcing functions in relation to climate variability and change will require the design and maintenance of a long-term observation system at the margins of several strategically located glaciers around Greenland.

Technological innovations are required to allow the collection of observations that are not at present possible; for example, to quantify submarine melting and to understand the dominant controls on calving. A particular concern common to the ocean and ice-sheet modelling communities is the requirement of improved bed maps (outlet glaciers, fjords and continental shelf).

Climate change and GrIS mass loss

Projections of atmospheric circulation changes, including the North Atlantic jet stream characteristics, associated changes in surface temperatures, and implied surface melting on the GrIS are key to inferring magnitudes of source waters that feed subglacial discharge. Evidence for polar amplification (that is, the above-global average increase in Arctic near-surface temperatures) has been found in observations and climate model simulations[76,77]. This implies that subglacial discharge may increase significantly, due both to increased surface melting and to an extended summer melt season. To what extent polar amplification in the coming century might be, in part, offset around Greenland by a reduction in poleward oceanic heat transport — possibly due to changes in the structure of the AMOC — is at present unclear[78].

Ancillary to the projection of subglacial discharge are the required modelling capabilities of the surface, englacial and sub-glacial drainage system, as well as the connection between glacial hydrology, geometry, submarine melting and calving[79–81]. An understanding of these processes remains in its infancy and an important research focus in the coming decade. Enhancing observational capabilities will require technological advances not unlike those made in the design of space missions to conduct autonomous measurements in 'remote' and hostile environments. Model simulations are faced with the challenge of bridging roughly seven orders of magnitudes of scales, and representing different physical processes (ice–ocean boundary layer to North Atlantic basin scale; Fig 4) — they need to solve multiscale and multiphysics problems.

Quantification of future contributions of oceanic heat delivery to the margins of the GrIS is tied to skilful projections of North Atlantic Ocean circulation changes, which are strongly tied to atmospheric circulation changes[82]. In addition, long-term changes in oceanic heat uptake, storage, and transports contribute to a spatio-temporally complex warming pattern around Greenland. The skill of climate model projections remains at present difficult to quantify, and results depend on future emissions scenarios. A suite of climate model projections (CMIP3) from the IPCC Fourth Assessment Report suggest warming of relevant subsurface (200–500 m) water masses that are substantially larger compared with recent warming rates, and which eventually penetrate to the northern margins of the GrIS[78]. The implication is that outlet glaciers in northern Greenland that at present support 'floating ice tongues' and show little mass loss (Petermann glacier in the northwest and outlet glaciers of the Northeast Greenland Ice Stream) may become more vulnerable to oceanic forcing. Serious limitations of heat content estimates (such as the one in Fig. 2)[32,75] are their construction from sparse and uneven spatio-temporal sampling of the global ocean. Concerted efforts are required to establish and sustain a global ocean-observing framework that satisfies stringent climate-quality requirements[83].

GrIS mass loss and North Atlantic climate

Finally, we shift the focus from how Greenland responds to climate change to what potential impacts the mass loss has on the climate system. On decadal to centennial timescales the two main perceived effects are sea-level change — directly through oceanic mass increase and its spatio-temporal adjustment due to changes in ocean dynamics[84,85], and indirectly through glacial isostatic adjustment (Box 1) effects[86] — and the impact of surface freshening on the AMOC, its associated meridional heat transport and effects on climate[87–90].

Very large conceptual discrepancies remain between impact studies of North Atlantic freshening in terms of magnitudes of freshwater fluxes considered (between 0.01 and 1 Sv), input locations (coastally confined compared with spread out over the interior) and model resolutions considered. Simulations with eddy-permitting models (spatial resolutions of 10 to 25 km) show very different response patterns compared with those realized by current generation climate models (about 100 km). However, none of these studies resolve the first baroclinic Rossby radius of deformation (about 7 km), casting doubts as to whether exchange processes between the boundary currents and the interior (in particular through mesoscale eddies) are correctly represented[91]. The amount of freshening that reaches the interior convection sites (together with gradual transformation of Atlantic water masses in the boundary currents) may determine the degree to which the North Atlantic circulation responds, its impact on the atmospheric circulation and potential climate shifts over the continents.

Discussions regarding sea-level implications are already available[92], and so our focus is on mass loss projections. The absence of available coupled climate–ice-sheet models that are able to resolve outlet glacier flow, include accurate ice-flow dynamics and ice physics (in terms of glacial hydrology, calving models, ice–ocean coupling and moving ice–ocean interface), has led to attempts to provide Greenland mass loss estimates, either through consideration of upper bounds on physically feasible ice flow[13,93], or lower bounds from observed present-day perturbations[94], or forced simulations with current-generation ice-sheet models of varying complexity[95–97]. The range from 0.01 m to 0.54 m of eustatic sea-level rise until 2100 from Greenland ice dynamics reflects the current uncertainties in these projections. It is important to remember that regional sea level is the variable of more direct societal relevance for coastal communities, and which may exceed the global mean considered here by a factor of five[91]. A serious limitation to the verification, validation and calibration of ice-sheet simulations is the near-absence of crucial measurements of conditions in the interior and at the bed. Ice-sheet modelling, therefore, represents a grand challenge computational inverse problem.

An inter-generational scientific challenge

Reducing the uncertainty in projected contributions to sea-level rise from Greenland ice dynamics, as well as ascertaining the reliability of estimated upper bounds requires detailed cross-disciplinary process understanding and vastly improved simulation capabilities in all of the aspects discussed in this Review. Such understanding can only come through much expanded, internationally coordinated observational assets, both at the small-scale process level, and of large-scale circulation changes. It involves the design and deployment of new instruments on the ground, at sea and in space; the maintenance of crucial *in-situ* and satellite observing systems; and the collection of geological records to allow the reconstruction of palaeo-ice-stream evolution through the Holocene. These should be accompanied by rigorous approaches to synthesize the heterogeneous data streams into a coherent dynamic framework[98]. Sustaining such observations over sufficiently long periods to provide records of useful quality for climate research[99] is a serious inter-generational challenge[100]. ■

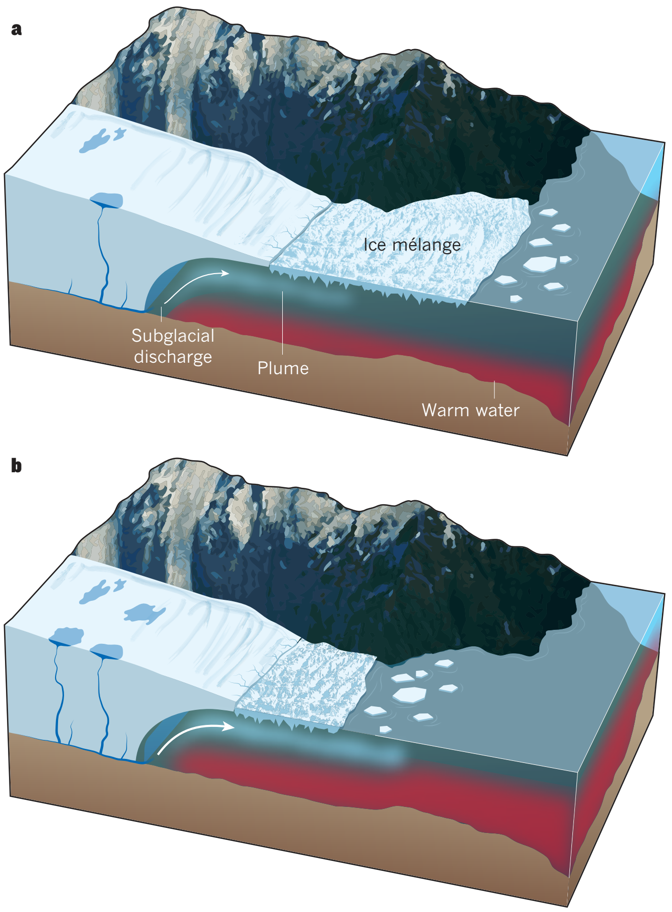

Figure 5 | Submarine melting. Warming subsurface ocean waters and increased glacier surface melt resulted in increased submarine melting and, potentially, a weakened ice mélange at the marine margins of Greenland's outlet glaciers. **a**, Pre-retreat conditions include relatively cold waters, limited subglacial discharge and a thick ice mélange. **b**, Retreat conditions include warm fjord waters, increased subglacial discharge and weakened mélange.

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